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GEOLOGY OF THE ETTA SPODUMENE MINE, BLACK HILLS, SOUTH DAKOTA.

G. M. SCHWARTZ.

INTRODUCTION.

THE Etta mine is known the world over as a deposit containing huge crystals of spodumene, undoubtedly the largest thus far discovered anywhere. It is also worthy of note that it is, at present, the most important producer of lithium ore in the United States. Although the mine has been repeatedly referred to, and briefly described, no complete description has appeared since the large openings made by war production. This paper is based on a field study made during brief visits to the region in 1921, 1922, and 1924, and on subsequent studies in the geological laboratory of the University of Minnesota.

Acknowledgments are due to Mr. James Cessna, Superintendent of the Etta, for permission to study and map the mine and for many mineral specimens. I am especially indebted to Mr. R. J. Leonard for much assistance in the field and analytical work.

GENERAL FEATURES.

History of the Mine.—Previous to 1883 the Etta claim had been worked for mica. In that year Mr. W. P. Blake[1] determined tin in samples from the Etta mine which had been submitted to him for analysis. In 1884 the claim became the property of the Harney Peak Tin Mining, Milling, and Manufacturing Company, but the company later failed. After some years the Etta property was leased for mining spodumene, and production apparently began in 1898,[2] continuing more or less actively

[1] Blake, W. P., "The Discovery of Tin-stone in the Black Hills of Dakota," *Eng. and Min. Jour.*, vol. 36, pp. 145–6 and 163–4, 1883; "Tin Ore in the Black Hills of Dakota," *Min. Res. of the United States*, 1883–4, pp. 602–613.

[2] O'Harra, C. C., "Mineral Resources of South Dakota," Dakota Geol. Survey Bull. 3, 1902. Also South Dakota School of Mines Bull. 6, 1902.

easily and rapidly under the influence of varying solutions with which they may be in contact, in such a way that a sodium zeolite in a solution of $CaCl_2$ changes to a calcium zeolite by exchange of 2 Na for Ca, and changes back again if then immersed in a solution of NaCl. This change of composition (after formation) is unlike the possible variation of composition when first formed, and may therefore be recognized. When discovered, it leads to an inevitable conclusion regarding the character of the solutions in which the zeolite was last immersed, as well as giving a clue as to the character of the solutions from which it formed.

In another case the nature of the chemical change is different. Evidence is available which points to the conclusion that in ferriferous chlorite, and presumably in other hydrous silicates which contain iron, the state of oxidation [4] of the iron may change without destroying or materially changing the crystalline space-lattice. This, also, is a change which is only possible after formation of the crystal, and therefore indicates the activity of reducing or oxidizing solutions.

Such changes constitute a type of metamorphism which is "new" in the sense that it is characterized by a feature which has not been recognized hitherto in nature. This feature is the change of composition without destruction of the crystalline space-lattice.

At the present time this conception is to some extent hypothetical; if correct, it seems to the writer that it will surely be useful in the study of ore deposits, and it is therefore presented in the hope that it may be tested as soon as possible, and perhaps in various ways. For example, if an ore deposit contains ferriferous chlorite, an analysis of that mineral should yield indications of a change in the oxidizing or reducing character of the solutions which have affected the deposit since the formation of the chlorite, if such a change occurred while the solutions were still warm or hot. Recent experiments indicate that cold solutions are not effective agents in producing such changes in chlorite.

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[4] See *Science*, vol. LXII, 1925, p. 311, for proof from an unexpected source that the state of oxidation of iron in magnetite may be changed without destroying or materially changing the crystalline space-lattice.

for five or six years and then only intermittently until the world war increased the demand for lithium. In 1909 Hess [3] reported that the Standard Essence Company of Maywood, New Jersey, had worked the deposit for some years. During the war, mining was active and a large area of the deposit was exposed. Since the war, mining has been continuous, but not particularly active. The mine is now controlled by the Maywood Chemical Company of Maywood, New Jersey.

The Mine.—Until the past year all of the mining was by open pit methods although a tunnel had been run at depth to test the extension of the deposit and also for drawing ore from the pit. Recently operations have been started underground in a stope above the lower tunnel and the small production is coming from this stope. The rock is blasted and the spodumene sorted by hand picking. The waste, consisting principally of feldspar and quartz, is dumped as much as possible in piles composed of one mineral. Early in 1924 some of the feldspar dumps were being sorted and the feldspar shipped to Chicago. Small amounts of columbite and other minerals are also sorted and sold when there is a demand.

Location and Topography.—The Etta mine is located about a mile south of the village of Keystone, Pennington County, South Dakota, at an elevation of 4,500 feet above sea level, and six miles northeast of Harney Peak, the highest point in the Black Hills. (Elevation 7,240 feet above sea level.) The Hermosa topographic sheet of the United States Geological Survey shows the location of the mine and its relation to the surrounding country. It is situated on a knob between two gulches which join just below. (See Plate A, Bull. 6, S. D. School of Mines.) The surrounding country is very rugged, the granites and pegmatites forming hills and mountains. The Black Hills branch of the Burlington railroad passes through Hill City, ten miles to the west, and a spur extends to Keystone.

Previous Descriptions.—So many papers have referred, at least briefly, to the deposit that only the more important are

[3] Hess, F. L., *Min. Res. U. S.*, 1909, vol. 2, p. 651.

listed here. The first and most complete descriptions were by Blake.[4] Later Headden,[5] Hess,[6] and Ziegler[7] added much data. Runner and Hartman[8] have more recently noted some features in connection with the occurrence of tungsten in the pegmatites of the region.

ASSOCIATED ROCKS.

The Harney Peak Granite.—The spodumene of the Etta mine occurs in one of a great series of pegmatites found in the area surrounding the Harney Peak granite which forms the core of the Black Hills uplift. No map has been published which gives the outlines of this granite mass in detail, but Newton[9] shows it as having a roughly oval outline of about seven by ten miles. These certainly are maximum dimensions since much of the area outlined is known to be occupied by pre-Cambrian schists in which the granite is intruded. It is classed as pre-Cambrian by all investigators who have mentioned its age.

The parts of the granite seen by the writer are largely pegmatitic. Schist inclusions of all sizes are abundant even on Harney Peak, the center of the granite area. This indicates that the granite is the upper part of a batholith. Ziegler[10] has stated: "The high acidity, the presence of the minerals characterized by the mineralizers, the coarseness in grain, and the variability in the mineral makeup, as well as geological conditions, seem sufficient proof to the writer that the exposed portions of the granite

[4] *Op. cit.*

[5] Headden, W. P., "Note upon the Discovery and Occurrence of Tin in the Black Hills," *Proc. Col. Sci. Soc.*, vol. 3, pp. 347–350, 1890.

[6] Hess, F. L., "Tin, Tungsten, and Tantalum Deposits of South Dakota," U. S. Geol. Survey Bull. 380, pp. 131–163, 1909; *Min. and Sci. Press*, vol. 100, p. 822, 1910.

[7] Ziegler, V., "The Minerals of the Black Hills, South Dakota," South Dakota School of Mines Bull. 10, 1914; *Min. and Sci. Press*, vol. 108, pp. 604–8, 654–6, 1914.

[8] Runner, J. J., and Hartman, M. L., "The Occurrence, Chemistry, Metallurgy, and Uses of Tungsten," South Dakota School of Mines Bull. 12, 1918.

[9] Geological map of the Black Hills, 1879. But see U. S. G. S., folio No. 219 (in press).

[10] Ziegler, V., "The Differentiation of a Granitic Magma as shown by the Paragenesis of the Minerals of the Harney Peak Region, South Dakota," Econ. Geol., vol. 9, pp. 264–277, 1914.

represent only the marginal zone of a granite batholith, probably its upper zone laid bare by erosion."

Ziegler describes the granite as soda rich, high in quartz and muscovite, with orthoclase, microcline, and albite, as the chief feldspars. He took a special phase from near Custer as representing most closely the Harney Peak magma. It is characterized by alkali feldspars, biotite, muscovite, and about 8 per cent. quartz. The accessory minerals in the order of their importance are: apatite, zircon, magnetite, and titanite.

The writer collected two specimens which seemed to him to represent most nearly normal granite phases. The first, from the top of Harney Peak, is a granite with a medium to fine texture, and many black needles of tourmaline. Microcline and oligoclase feldspar, with microcline predominating, make up about 60 per cent. of the rock. Quartz, with accessory tourmaline, muscovite and garnet compose the remainder. The tourmaline is blue, varying to nearly colorless. The second rock was obtained from a road cut between Hill City and Sylvan Lake. It is a gray, medium-grained rock with from 60 to 65 per cent. oligoclase and microcline, about 25 per cent. quartz and 5 per cent. each of biotite and muscovite. An occasional pink garnet is the only accessory.

The Schists.—The Harney Peak granite is intruded in a series of pre-Cambrian metamorphic rocks which show considerable variation. Ziegler [11] has noted the following types near the granite: phyllites, mica schists, staurolite schists, actinolite schists, garnet schists, tourmaline schists, graphite schists, mica gneisses, amphibolites, and quartzites.

The Etta pegmatite is intruded in a rather fine-grained gray schist consisting principally of quartz and biotite with occasional grains of garnet, muscovite, and tourmaline. At places not far from the mine large staurolite metacrysts are found in a schist which otherwise appears like that just described.

At the contact of the pegmatite and schist the latter has been intensely altered in a zone averaging 5 feet in thickness. (See Figs. 1 and 2.) A detailed study of this metamorphism must

[11] Ziegler, V., Econ. Geol., vol. 9, p. 265.

be left for a later paper, but some of the features may be outlined here. The schistosity is, for the most part, destroyed and a granular sugary rock developed which shows variations from place to place around the periphery of the pegmatite. As a rule the contact is sharp between the pegmatite and the intruded rock which grades from the sugary phase to the normal schist. However, at places there is an alteration of pegmatite and contact rock or schist. The most striking phase of the contact rock consists of biotite plates as much as two inches across embedded in a gray sugary matrix of quartz, microcline, plagioclase, garnet, muscovite, and tourmaline. Quartz and microcline are abundant and enclose the other minerals noted. The biotite and tourmaline are especially noteworthy as they were not observed within the pegmatite proper. Along the east wall of the pit a tourmaline schist is especially abundant. The principal mineral is tourmaline. Quartz is abundant and is embedded in a matrix or network of tourmaline forming a mosaic. A common phase is a fine granular rock consisting of quartz and feldspar with minor amounts of tourmaline, garnet, and muscovite.

The contact action is remarkable for its intensity over a zone which is so narrow and grades quickly to schist which is little different from that at a considerable distance from any exposed intrusive. The small size of the pegmatite makes the severe effect the more remarkable but the highly pegmatitic nature of the mass doubtless offers the explanation.

Distance of Pegmatite from Granite.—Time did not permit a detailed study of the east side of the batholith to determine the exact boundary, but a large mass of granite stands at a considerable elevation about one and one half miles west of the Etta mine. This is roughly the horizontal distance of the mine from the exposed granite, but the abundant pegmatite masses of various types and shapes indicates that the granite may not be far below in the region of the mine. From a distance, outcrops near the mine appear to be granite, but on close examination they are found to consist of coarse pegmatites.

THE PEGMATITE.

General Relations.—The pegmatite which forms the Etta deposit is one of a great series which are distributed on all sides of the Harney Peak granite. Of these the group at Keystone is perhaps the greatest. These pegmatites and their minerals have been described in considerable detail by Ziegler [12] and Hess.[13] The mines have produced on a commercial scale: lithium (in the form of spodumene, amblygonite, and lepidolite), tungsten, mica, rose quartz, feldspar, beryl and small amounts of tantalum and columbium incidental to other mining. Tin has been the cause of more explorations than those noted, but thus far little has been produced.

The Etta pegmatite is not connected at the surface with other pegmatites but they are found on all sides near it, the Hugo mine pegmatite being only 1,000 feet to the west.

Size and Shape.—The pegmatite is roughly oval in outline with diameters at the plane of the lower tunnel of 200 and 250 feet, with a pronounced indentation on the east side due to a mass of schist. The pegmatite extends 125 feet above the lower tunnel, but was much higher before being destroyed by mining. Figs. 1 and 2 show the form of the deposit in plan and cross-section. Diamond drill holes have been put down from the lower tunnel and indicated that the deposit closes in about 100 feet below. It seems unlikely that the pegmatite ends entirely at this depth, but will probably have at least a small connecting dike beneath.

Structure and Texture of Pegmatite Mass.—Of the repeated descriptions of the Etta deposit only one has ever shown a sketch of the structure of the mass. This was by Blake [14] in one of the

[12] Ziegler, V., "Lithia Deposits of the Black Hills," *Eng. and Min. Jour.*, vol. 96, pp. 1053–1056 and 1088, 1913; "The Mineral Resources of the Harney Peak Pegmatites," *Min. and Sci. Press*, vol. 108, pp. 604–608 and 654–656, 1913; "The Minerals of the Black Hills," South Dakota School of Mines Bull. 10, 1914.

[13] Hess, F. L., "Tin, Tungsten, and Tantalum Deposits of South Dakota," U. S. Geol. Survey Bull. 380, pp. 131–163, 1909; *U. S. Min. Res.* for 1909, pp. 649–653; "Lithium and its Sources," *Min. and Sci. Press*, vol. 100, pp. 822–824, 1910.

[14] Blake, W. P., "Tin Ore in the Black Hills of Dakota," *Min. Res. of the United States* for 1883–1884, pp. 602–613.

earliest articles. His sketch showed four zones as follows, beginning with the outer: (1) Biotite and muscovite, (2) crystals of spodumene, greisen and tin-stone, (3) greisen and tin-stone, (4) quartz and feldspar. This referred to the upper part of the knob and does not apply to the deposit as now exposed.

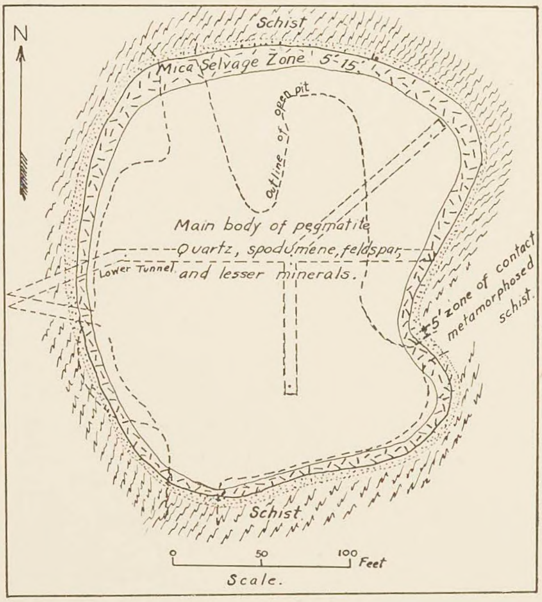

FIG. 1. Plan of the structure of the Etta pegmatite at the level of the lower tunnel.

As previously noted, the schist at the contact is much altered to a coarse sugary rock which at places contains coarse biotite, and other places much tourmaline. Undoubtedly the schist is much changed by additions from the pegmatite but the apparent absence of biotite in the pegmatite proper suggests to the writer that at least the iron of the biotite came from the schist. This occurrence of the mineral may account for Blake's statement that it occurred in the outer zone. The outer zone of the pegmatite is normally five or more feet thick, but rarely, if ever, over fifteen. It consists principally of muscovite with quartz and some feldspar. It has been described [15] as approaching the composi-

[15] Ziegler, V., *Eng. and Min. Jour.*, vol. 96, p. 1053, 1913.

tion of a typical granite. This seems misleading as muscovite is by far the most important mineral and feldspar is subordinate to quartz. The writer has adopted the phrase "mica selvage zone" as conveying the idea of the nature of this material. This outer zone grades quickly to the main body of the pegmatite

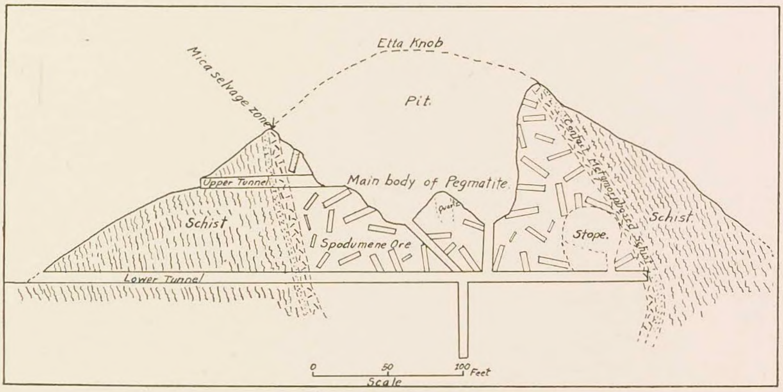

FIG. 2. Cross-section of the Etta pegmatite along line of the lower tunnel.

within which no definite zoning can be distinguished at present. This main body is made up of an extremely coarse mass of quartz, feldspar, and spodumene with lesser amounts of muscovite, lepidolite, beryl, columbite, lithiophylite, and other minerals. No regularity is discernible. Huge crystals of spodumene resembling logs lie in every direction. These vary in size from a foot or two in length to thirty and even forty feet. The largest recorded was forty-two feet long, from three to six feet in diameter, and contained thirty-seven tons of spodumene. At places now well exposed on the south wall of the pit are star-like aggregates of spodumene crystals radiating from a center which is often a mass of muscovite. Normally the spodumene crystals are embedded in masses of milky quartz and imprints of the crystal faces are left when the spodumene is removed. The crystals often cross and one is cut and somewhat altered at the intersection, indicating that the later crystal had grown through the earlier. Alteration is common at these intersections. At places

are masses of quartz and feldspar, or quartz alone, practically free from spodumene. These barren areas, however, are apparently not confined to a definite zone, but are in the nature of horsts.

MINERALOGY.

The number of minerals listed as occurring in the Etta mine is very large, but many are rare and can not be observed by a casual visit. The principal minerals are: spodumene, quartz, feldspar (albite, microcline, and oligoclase), and muscovite.

ANALYSES OF MINERALS FROM THE ETTA MINE.

	1	2	3	4	5	6	7	8	9	10
SiO_2	62.91	63.79	66.65	44.87	44.23	1.00				2.00
Al_2O_3	28.42	20.13	21.51	36.77	37.49	n.d.				
Fe_2O_3	.53	.22		1.70	1.60	1.80				
FeO	n.d.	n.d.	n.d.	n.d.	n.d.		8.28	8.59	8.33	7.30
MgO	.13	.38	.08	.72	.18					
CaO	.11	.25	.05	.10	.08		.88			
Na_2O	.46	2.39	10.42	.60	.68					
K_2O	.69	12.55	.71	10.37	10.26					
Li_2O	6.78	n.d.	n.d.	.38	.22					
H_2O+	.28	.24	.30	4.72	5.80					.40
TiO_2										47.80
Cb_2O_5							40.37	39.94	none	6.20
Ta_2O_5						2.42	41.14	42.96	79.01	34.80
SnO_2						94.36	.13	tr.	.39	1.30
MnO							9.09	8.82	12.13	
	100.31	99.55	99.72	100.23	100.54	99.58	99.89	100.31	99.86	99.80
Sp. G.	3.167	2.554	2.622	2.855	2.818					

1. Spodumene from a large crystal cut by lower tunnel. Analyst R. J. Leonard.
2. Microcline. Unaltered cleavage fragments. Analyst R. J. Leonard.
3. Albite. Fresh fragments showing curved lamellæ. Analyst R. J. Leonard.
4. Mica. Fine greenish-colored aggregate like lepidolite. Analyst R. J. Leonard.
5. Mica. Coarser light greenish-colored aggregate. Analyst R. J. Leonard.
6. Cassiterite. First mass found in Etta mine. Headden, *Proc. Col. Sci. Soc.*, vol. 8, p. 167 (1916).
7. Columbite. One of a group of crystals weighing 30¼ pounds. Headden, *Am. Jour. Sci.*, vol. 41, p. 95 (1891).
8. Columbite. Crystal weighing 14 pounds. Headden, *Am. Jour. Sci.*, vol. 41, p. 95 (1891).
9. Tantalite. Shaeffer, *Trans. A. I. M. E.*, vol. 13, p. 232 (1884).
10. Struverite. Hess and Wells, *Am. Jour. Sci.*, vol. 31, p. 442 (1911).

Others which may be easily found on the dumps include columbite, tantalite, lepidolite, apatite, beryl, lithiophylite, cassiterite, triphylite, and opal. In addition the following have been mentioned in published articles, or were seen by the writer: struverite, cuprocassiterite, stannite, malachite, purpurite, scorodite, heterosite, tapiolite, amblygonite, biotite, leucopyrite, tourmaline, autunite, triplite. Many others have been found in the pegmatites of the region as noted by Ziegler.[16]

Spodumene.—The occurrence of spodumene has been described in some detail above. Although this is the most important known occurrence of the mineral, no analysis of it from this locality has been published. Ziegler [17] records the determination of lithia of three specimens as 6.16 per cent., 3.56 per cent., and 1.18 per cent. respectively. Mr. R. J. Leonard has made a complete analysis of almost perfectly fresh material obtained from a large crystal cut by the lower tunnel. (See table of analyses.)

Microscopic examination of thin sections and powdered mineral shows the uniformity of the material. The powder shows excellent cleavage fragments, the large ones being somewhat clouded by minute fractures. The maximum extinction angle measured on these fragments is 31° which is somewhat above that given in published tables. (Winchell gives 26° and Larsen 24°.) Considerable dispersion is shown by some fragments and this also is at variance with published data.

The spodumene alters quickly on exposure and develops a fibrous structure. Some crystals have altered to a greenish talc-like mass whereas the fresh material is almost transparent. The writer and Mr. Leonard are preparing a paper describing the alteration in detail and including analyses of a gradational series of specimens.

Mica.—The Etta mine was worked for mica previous to 1883. Large plates of muscovite are common and the "selvage zone" described above is composed dominantly of interlocking muscovite plates up to two inches across. This varies from colorless to a light green. The fine-grained phases of the pegmatite contain

16 *Op. cit., Min. and Sci. Press,* vol. 108, pp. 604–608, 1914.

17 Ziegler, V., South Dakota School of Mines Bull. 10, p. 152 (1914).

small light greenish mica flakes. At places are masses of fine mica scales approximately a millimeter across and practically pure. This has a decided green color and was labeled lepidolite as Ziegler states that green lepidolite is found in the Etta mine.[18] More common are aggregates of flakes about 5 mm. across and of a lighter green color. This was labeled lepidolite with a question. Mr. Leonard has analyzed these green specimens and shows conclusively that they are not lepidolite (Analyses Nos. 4 and 5), but muscovite. Under the circumstances there is doubt as to the existence of green lepidolite in the Etta and other pegmatite mines of the region.

Biotite was found in the metamorphosed schist within a few feet of the contact, but was not recognized in the pegmatite.

Feldspar.—The principal feldspar in the pegmatite is microcline, but some albite is found at places and oligoclase has been noted by other investigators. Microcline with milky quartz forms the principal part of the matrix in which the huge spodumene crystals are embedded. An analysis given in the table is of interest in connection with the recent commercial use of the material at Chicago. The content of soda is decidedly lower and the potassium higher than that of most feldspar on the market. A microscopic examination indicates the presence of the soda as albite included in the microcline.

Albite occurs as masses showing the characteristic curved lamellar form. It has a decidedly dark gray cast in large fragments. The powder shows few twinning bands, probably due to its coarseness. The analysis given in the table shows it to be unusually pure, being especially free from calcium and having a relatively low potassium content. Albite was not noted in large amounts either on the dumps or in the mine except in fine aggregates with mica, quartz, apatite and small specks of cassiterite. These aggregates occur as masses in the coarser pegmatitic material exposed in the pit. Fine muscovite scales are found along some of the cleavage faces of the large masses.

Cassiterite.—As previously noted, the occurrence of cassiterite

[18] Ziegler, V., South Dakota School of Mines Bull. 10, p. 177 (1914).

first attracted notice in the Etta mine in 1883. Blake [19] states: "The first masses of tin ores were embedded in the midst of the crystals of spodumene and of feldspar, and yielded fragments of nearly pure cassiterite weighing from one to fifty pounds or more. The chief associate or gangue of the tin ore is, however, a dense aggregation of small crystals of mica, of a light yellow color, forming irregular veins and bunches in the midst of the granitic mass. In this micaceous rock, formed of the mica with a white spar apparently albite, the tin ore is disseminated in grains from the size of a mustard seed to the size of peas, and sometimes an inch in diameter."

Headden has given an analysis of the first large mass found which shows it to be comparatively pure SnO_2. (See table.) At the present time cassiterite is comparatively uncommon and usually is found only as small grains, although other prospects in the region yield good specimens. Mr. James Cessna [20] reported that cassiterite was rather abundant in the upper part of the deposit, but is not found in any amount now.

Columbite-Tantalite.—These minerals commonly occur as isomorphous mixtures and this occurrence is not an exception. Columbite was recognized at an early date by Blake.[21] Later Shaeffer [22] analyzed a sample submitted to him and found it to be nearly pure tantalite. (See analysis No. 9.) Several brief papers on the minerals appeared and Headden [23] reported a very complete study of the two minerals with many analyses. Two typical ones from the Etta mine are given in the table. From descriptions it is apparent that columbite-tantalite like cassiterite was abundant in the upper part of the mine. Columbite (or columbite-tantalite) may be found in considerable masses at the

19 Blake, W. P., "Cassiterite, Spodumene, and Beryl in the Black Hills, Dakota," *Am. Jour. Sci.*, vol. 26, p. 235 (1883).

20 Personal communication.

21 Blake, W. P., "Columbite in the Black Hills of Dakota," *Am. Jour. Sci.*, vol. 28, p. 340 (1884); "Tantalite and Columbite in the Black Hills of Dakota," *Trans. Am. Inst. Min. Eng.*, vol. 13, p. 696 (1885).

22 Shaeffer, C. A., "Note on Tantalite, etc.," *Trans. Am. Inst. Min. Eng.*, vol. 13, pp. 231–233 (1884).

23 Headden, W. P., "Columbite and Tantalite," *Am. Jour. Sci.*, vol. 41, pp. 89–102 (1891).

present time. During the war the material was picked out and shipped. The crystals often show what is apparently an oscillatory combination on one side of a tabular crystal.

The other minerals listed are not particularly abundant nor commercially important, and need not be described here. Details on them are available in the references cited in this paper.

CONDITIONS OF FORMATION.

That the deposit which forms the Etta mine is a pegmatite which originated by the offshoots of the more mobile parts of a granite mass is obvious. There are, however, some unusual features of this and other pegmatites in the region which may be noted. The huge crystals of spodumene in the Etta are so large, even for pegmatites, that some abnormal conditions must have prevailed at the time of formation which resulted in what might be termed superpegmatites. The key to the reasons for these unusual deposits is the nature of the Harney Peak granite mass. The pegmatitic nature and lack of a normal granite phase has been emphasized. In fact it would not be far from correct to refer to all the exposed Harney Peak granite as a pegmatite. The writer believes that this granite was possessed of an unusually high content of volatile constituents and that the parts rejected by crystallization of the main mass at depth were of great quantity and extremely mobile. The great series of pegmatites, some several miles from exposed granite, seem proof of this. Before considering the direct cause of the formation of the huge spodumene crystals, it should be emphasized that other minerals of the deposit show very large crystals and masses but less perfect and striking than in the case of spodumene. Columbite forms large crystals in the Etta and occurred as masses of 600 pounds.[24] Cassiterite was also found as large masses in the upper part of the deposit. At the Hugo mine, 1,000 feet west of the Etta, are masses consisting of many tons of feldspar which appear remarkably pure. Crystals of tourmaline several inches across are also found there. Masses of very pure amblygonite, lepidolite, and beryl, aggregating tons, are found in the Bob Inger-

24 Hess, F. L., U. S. Geol. Survey Bull. 380, pp. 131–161, 1909.

soll mine. Other examples might be cited. This segregation of the minerals, even within a single deposit, into large masses indicates not only extreme mobility, but a sort of mass action on a tremendous scale so that crystallization once started continued until all the material of the proper composition for a considerable radius was concentrated into one mass. In the case of spodumene this meant into crystals, commonly ranging from ten to forty feet in length.

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MODE OF FORMATION OF THE PORCUPINE QUARTZ VEINS.

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INTRODUCTION.

THE most ambitious recent attempt to explain the mode of formation of gold-quartz veins is by Spurr in his Ore Magmas and auxiliary writings. Spurr sees in the so-called "pegmatitic" (coarse-grained) quartz veins, strong analogies with igneous dikes and reasons that the mode of formation is similar for both. He contends that the quartz "vein-dikes" have been formed by forcible injection, the injected "ore magma" distending the walls of the invaded fissure. Some other geologists believe that quartz veins have grown by the force of crystallization; that the growing crystals themselves, rather than the vein fluids, have exerted pressure on the walls of fissures and have forced these walls apart. Others maintain that the major process is simply open fissure filling. Still others imagine a growth of the veins "by permission," that is the opening of fissures by external stress, and as they widen, the simultaneous filling of these fissures by vein substance. Another group believe the process is mainly a chemical one; that the quartzose fluids have dissolved the invaded rock along the walls of fissures and have solidified in the spaces thus produced.

The Porcupine district of Ontario, Canada, is a fertile field for study of gold-quartz vein phenomena. Within the mines are numerous clear exposures of quartz veins and lodes of extraordinary diversity and complexity, cutting rocks of strongly developed physical characteristics, thus affording unusual opportunity for fruitful structural studies of the lodes and rocks.

As a basis for discussion I have selected the more instructive examples from a series of sketches and photographs made by me